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A Comparison of N Reactor and Chernobyl

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ABSTRACT

The nuclear reactor accident at Chernobyl in the Soviet Union has resulted in a number of design reviews of the Hanford N Reactor because of some similarities between N Reactor and the Soviet RBMK reactor. While the two reactors have some common features, they also have many significant differences. In addition, the reactor characteristics associated with the common features are very different. This report compares key system design and operating features and points out the differences in N Reactor and the RBMK. A description of the Chernobyl accident provides a basis to show how the differences in the two reactors and the manner in which they are operated would preclude a similar accident in the N Reactor.

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ACRONYMS

AR	Automatic Power Regulating Rods
ATWS	Anticipated Transient Without Scram
DOE	Department of Energy
ECCS	Emergency Core Cooling System
FCI	Fuel Coolant Interactions
FWHM	Full Width at Half Maximum
GSCS	Graphite and Shield Cooling System
LAR	Local Automatic Power Regulating Rods
LOCA	Loss of Cooling Accident
NRC	Nuclear Regulatory Commission
NUSAR	N Reactor Updated Safety Analysis Report
PRA	Probabilistic Risk Assessment
TG	Turbine-Generator
TMI	Three Mile Island

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I. SUMMARY

The Chernobyl plant Unit No. 4 was destroyed in April 1986 by an energetic power excursion caused by a combination of the Soviet RBMK plant design features and operator disregard of procedures and administrative controls. Because of perceived similarities, i.e., graphite moderated and water cooled, the N Reactor at Hanford has been subjected to a multitude of safety reviews to ensure that the conditions leading to the Chernobyl Unit No. 4 accident cannot occur in N Reactor. The review covered in this report was performed to evaluate N Reactor on the basis of our knowledge of the key factors leading to the Chernobyl accident and the lessons learned from it. The dominant conclusion is that the N Reactor design makes it physically impossible to have an autocatalytic reactivity excursion such as the one which destroyed the Chernobyl plant. In addition, N Reactor procedures and practices impose controls which would prevent the kind of procedure violations which set up the Chernobyl accident.

In early 1987, reports of Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) evaluations of the Chernobyl accident became available. This review was based on those reports, which had not been available for previous consultants reviews. The DOE and NRC technical review shows that a positive coolant void reactivity coefficient is characteristic of the RBMK design. Violations of operating and test procedures led to rapid formation of steam in coolant channels, which combined with a slow-acting, ineffective scram system to produce a power excursion to 110 times the normal rating.

While the impossibility of an autocatalytic power excursion in N Reactor is recognized, other perceived similarities with Chernobyl are also clearly incorrect or irrelevant. It is now known that graphite in the core of the Chernobyl reactor, which represents the most quoted similarity to N Reactor, did not materially contribute to the occurrence of the accident. Also, all available evidence at this time indicates that hydrogen was probably not a factor in the process that destroyed the reactor. The key differences that separate N Reactor from the possibility of a Chernobyl-type disaster can be addressed in terms of design features, administrative controls, and review of accident vulnerability.

N Reactor design and safety features that represent key differences from the Chernobyl plant are:

- N Reactor's design inherently reduces power when the reactor cooling water temperature increases and especially if the cooling water should boil.

- N Reactor has two fast-acting scram shutdown systems, either of which would effectively stop a power excursion.

- N Reactor's emergency cooling system is independent of electrical power requirements.

- A second cooling system for the graphite is capable of providing long-term cooling even if both the normal and emergency cooling systems are lost.

- A confinement system, which encloses the entire nuclear steam supply system, retains radioactive material even if an accident occurs. The system incorporates water sprays that would limit or extinguish fires associated with an accident.

Administrative controls required at N Reactor establish the following basis for confidence in operations:

- There are, in place, multiple layers of protection between the limits set in standard operating procedures and conditions representing a safety risk.

- The operating staff is formally trained with emphasis on adherence to procedures and limits (called Process Standards). Operations management continually reinforces compliance to safety standards.

- Tests performed in the reactor are controlled by rigorous procedures and safety reviews, which ensure that the reactor operator's primary responsibility is plant safety rather than the test.

- No safety functions can be bypassed outside the bounds of acceptable and authorized limits, which ensure the safety of the plant is not reduced.

Since N Reactor is not vulnerable to an autocatalytic power excursion accident like Chernobyl, risks from other types of accidents have been considered:

- N Reactor has been subjected to a thorough safety analysis [N Reactor Updated Safety Analysis Report (NUSAR)] which covers even worst case accidents.

- An ongoing probabilistic risk assessment (PRA) by an independent government laboratory has revealed no unexpected accident sequences or initiators.

- Preventing several hypothetical accident sequences rests on ensuring the integrity of the coolant-carrying process tubes. Protection from multiple tube failures results because:

  - As-procured process tubes were conservatively designed.

  - Thorough analyses and examinations (both in-place and destructive examination of removed process tubes) confirm that acceptable safety margins are maintained.

- Effects of graphite distortion and seismic events were analyzed to show that design criteria are still satisfied.

- Process tube monitoring programs, recently enhanced, provide assurance that degradation will be detected before its limiting condition.

- Design margins are defined to ensure that failure of a single tube will not result in failure propagation.

In addition to the design and administrative features which protect against occurrence of a severe accident, there are provisions for dealing with major and minor emergencies at N Reactor:

- The reactor is located on a relatively remote site with over 35 miles to a major population center (compared to approximately 3 miles at Chernobyl).

- Formal plans are in place, and continually practiced in accordance with DOE requirements, for handling emergencies, evacuations and recovery operations in case of a severe accident.

- Onsite fire fighters and emergency crews are trained to deal with fires in radiation zones and radioactive materials.

II. INTRODUCTION

The nuclear reactor accident at Chernobyl in the Soviet Union has resulted in a number of design reviews of the Hanford N Reactor because of some similarities between N Reactor and the Soviet RBMK reactor. While the two reactors have some common features, they also have many different features. In addition, the reactor characteristics associated with the common features are very different. The purpose of the Sections III and IV is to compare the major features of the two reactors. The discussion covers both design features and some important operations features.

The importance of differences in the design and operating features between N Reactor and the Chernobyl plant is demonstrated in Section V. The Chernobyl accident sequence is described and the effect of the plant features involved in the accident are discussed. The N Reactor features that preclude a similar accident are highlighted.

III. DESIGN FEATURES COMPARISON

N Reactor and the RBMK are both graphite moderated, pressure tube reactors. Outside the two common features of graphite moderator and individual pressure tubes (fuel channels) the reactors have few common design features. Table III.1 presents a summary comparison of some significant design and safety features between N Reactor and the RBMK. Differences in the design basis for a number of safety features are identified, with expanded descriptions provided below.

A. MODERATOR

Both reactors use graphite as the neutron moderator. However, the moderator/fuel ratios are different, resulting in major differences in coolant void reactivity coefficient. In an RBMK, the moderator consists of graphite blocks 250 mm (9.8 inch) in cross section and 600 mm (23.6 inch) in length. Each block has a cylindrical hole along its axis for the fuel channels. The blocks are stacked tightly together. In N Reactor, the graphite blocks are stacked in a "Lincoln Log" fashion. Tube blocks run parallel to the fuel channels and filler blocks run perpendicular to them. Gaps between the blocks reduce the effective graphite density. These spaces also allow for passage of helium cooling gas and steam venting in the event of a tube rupture.

The ratio of graphite moderator to uranium fuel is larger in an RBMK than N Reactor. This results in an RBMK having optimum neutron moderation from the graphite alone. Because of this, the cooling water (which can provide neutron moderation) is not needed for moderation and, thus, has a negative effect on the neutron utilization in the core. The water absorbs neutrons and acts as a neutron sink. Therefore, when water is removed from the fuel tubes by boiling during normal operation or leakage, the neutron absorbtion decreases resulting in a reactivity (power) increase. This effect is referred to as a positive coolant void coefficient of reactivity, or simply positive void coefficient. The magnitude of the reactivity increase is a function of the fuel residence time, fuel enrichment, coolant void fraction, and the number of control rods present in the core.

In N Reactor the cooling water is a vital contributor to neutron moderation. The graphite alone does not provide for optimum neutron moderation. The coolant, therefore, provides a positive effect on neutron utilization. The positive effect of added moderation more than offsets the negative effect of neutron absorbtion. If water were removed from a fuel channel the loss of moderation would cause the reactivity (power) to decrease. N Reactor, therefore, has an inherent negative coolant void coefficient. There are no operating conditions that cause N Reactor to have a positive coolant void effect.

TABLE III.1. Summary of Key Similarities and Differences Between N Reactor and Chernobyl

	Basic Characteristic		Influence	
Feature	Chernobyl	N Reactor	Chernobyl	N Reactor
Void Coefficient	Positive	Negative	Unstable	Inherently Stable
Shutdown System	One system	Two systems	Higher ATWS* potential	Very low ATWS* potential
Rate of Shutdown	>15 second insertion	<3 second insertion	Speed of reactivity control dependent on partial rod insertion	Speed of control independent of rod position
Control Rod Design	Graphite follower attached to end of rod	No graphite follower	Initial reactivity increase for rod insertion from full out position	Rod insertion always decreases reactivity
Testing and Maintenance of Safety Circuits	Performed at power from control room	Performed at shutdown from control room	Safety systems routinely partially bypassed at power	Safety systems bypass at power is prohibited
Design Basis Accident	Large pipe breaks plus limited transients	Any pipe breaks plus any credible transient	Limited design basis for safety systems performance	Safety system performance designed for full range of credible events
Pipe Break Protection Assumption	Rely on "leak before break" to exclude many break locations	Assume maximum pipe break at all locations	No protection for many break locations	Protection for any break size and location
Fuel Design	Oxide fuel in pins	Metallic uranium bonded to zirconium cladding	Cladding fails rapidly on cooling interuption (LOCA**)	Fuel heatup to failure takes much longer time
Pressure Tube Orientation	Vertical	Horizontal	Disruption creates "chimney" through core	Disruption creates static graphite "crucible"

* ATWS = Anticipated Transient Without Scram
**LOCA = Loss of Cooling Accident

Table III.1 (Continued)

	Basic Characteristic		Influence	
Feature	Chernobyl	N Reactor	Chernobyl	N Reactor
Containment Philosophy	Segregated, does not include reactor and some piping	Large volume enclosing reactor and coolant system	No containment for core accidents	Effective confinement for all accidents
Containment Design Basis	Varies, depending on energy input	Low-pressure structure	Requires knowledge of energy release	Effective for all energy releases within design basis
Fission Product Retention Mechanisms	Suppression pool	Confinement-filtered Vent	No retention except for large pipe break events	Permanent retention for all events***
Siting Emergency Action Basis	Near population centers	Remote - Fewer than 200 people within 10 miles	Immediate offsite actions required	No immediate, major offsite actions required

***Some noble gas released through stack in certain accidents.

B. COOLANT

Both reactors use light water as the coolant. However, in an RBMK the coolant begins to boil about one third of the way up the fuel channel and exits with a void fraction of nearly 80%. For this reason the reactor is referred to as a boiling water reactor. N Reactor coolant does not boil. In this respect it is more like a pressurized water reactor. Both reactors operate at approximately the same coolant temperatures. N Reactor pressure is somewhat higher to prevent boiling.

C. FUEL CHANNELS

Both reactors use individual zirconium alloy tubes to contain the fuel within the reactor core. The RBMK tubes are oriented vertically and have a 9 cm (3.5 inch) diameter and a wall thickness of 0.4 cm (0.16 inch). N Reactor tubes are oriented horizontally and are 8.2 cm (3.2 inch) in diameter with a wall thickness of 0.7 cm (0.28 inch). There are 1661 fuel channels in an RBMK, and 1003 fuel channels in N Reactor.

D. FUEL

The RBMK uses uranium-oxide fuel arranged in two rings of zirconium-clad rods; six rods are in the inner ring and 12 rods are in the outer ring. Each fuel assembly consists of two 3.5-m (11.5-feet) long sections joined end-to-end. The uranium enrichment is 2 wt% U-235.

N Reactor uses uranium metal fuel arranged in a tube-in-tube geometry. The fuel is clad with a zirconium alloy by means of a coextrusion process that produces a mechanical bond between the cladding and the fuel. Seventeen elements approximately 0.6 m (23.6 inch) in length are loaded into each fuel channel. The core loading consists of fuel with two enrichments, 0.95 wt% U-235 and 1.25 wt% U-235.

E. CONTROL AND SHUTDOWN SYSTEM

Reactivity control for power control and shutdown in an RBMK is accomplished by 211 movable absorber rods. Additional reactivity control at the beginning of life is accomplished by placing fixed absorbers in approximately 300 of the fuel channels. As the initial reactivity decreases because of fuel burnup, the fixed absorbers are replaced with fuel. During equilibrium operation, about two or three years after initial startup, no fixed absorbers are required. At the time of the Chernobyl accident there was only one fixed absorber in place.

All but 24 of the 211 control rods are inserted from the top of the core. The other 24 are raised into the bottom of the core to assist in axial power control. When a control rod is pulled upward out of the core, a graphite follower is pulled along to displace the rod channel cooling water. Since the cooling water acts as a neutron absorber, the graphite follower reduces this unwanted loss of neutrons. If the control rod is pulled to its upper limit the 5 m (16.4 feet) long graphite follower is axially centered in the 7 m (23 feet) tall core which leaves 1 m (39.4 inch) of the rod channel at the bottom to be completely filled with water. When a fully withdrawn rod is inserted, the graphite follower initially displaces this water in the bottom 1 m (39.4 inch) of the core resulting in a local power increase during the first part of the insertion. In effect, the scram initially produces a reactivity increase, which is then followed by an overriding reduction in reactivity. This characteristic was likely a major contributor to the severity of the accident at Chernobyl.

Movement of the RBMK control rods is provided by a pulley and cable system. All rod insertion requires the unwinding of the cable from the pulley. As a result the rods require approximately 20 seconds to fully insert during a scram.

N Reactor has 84 horizontal control rods divided into two separate banks that enter from opposite sides of the reactor. That is, the rod motion is horizontal and perpendicular to the orientation of the fuel channels. The rods move in channels within the graphite moderator. These channels are open to the graphite stack cooling gas. The rod cooling water is an integral part of the rod itself; therefore, there is no need for a rod follower. Under no conditions can the insertion of an N Reactor control rod cause a reactivity increase.

A hydraulic system is used for movement of N Reactor control rods. Following a scram signal, rods are fully inserted within two seconds from their fully withdrawn position. Energy for this rapid insertion is provided by compressed-nitrogen hydraulic accumulators, one for each rod.

In addition to the control rod system, N Reactor has a fast response backup shutdown safety system. Vertical channels through the graphite moderator can be filled with boron-graphite balls to accomplish reactor shutdown. This system is activated if the rods fail to insert in the required time, if power is not rapidly reduced after scram or if the reactor is not rendered and maintained subcritical after scram. This safety system also would insert automatically from a seismic signal or a signal to activate the Emergency Core Cooling System (ECCS). The boron ball backup system performs its functions automatically without a need for operator action; however, the operator can activate the system (pushbutton). Insertion of either rods or boron balls will shut the reactor down and hold it down indefinitely.

F. REACTOR ENCLOSURE

An RBMK core is enclosed within a 1.6-cm (0.6-inch) thick cylindrical steel tank bounded on the top and bottom by 1-m (39.4-inch) thick steel and concrete shields. The zirconium alloy tube fuel channels and control rod channels are welded to the upper shield. Pressure relief for the reactor space is designed for the rupture of a single fuel channel tube. Rupture of more than one channel overpressurizes the enclosure. If several channels were to rupture, the overpressure would cause the upper shield to lift up. Since the fuel channels and rod channels are welded to the upper shield, any upward movement ruptures all the fuel channels and causes the control rods to be lifted out of the core. This characteristic was a major contributor to the severity of the Chernobyl accident.

The N Reactor core enclosure consists of concrete biological shields on the top and both sides. These shields are connected. The enclosure at the front and rear is not attached to the top and side shields and is designed to move as the Zircaloy fuel channel tube expands and contracts. The pressure relief system is designed to accommodate the rupture at power of a single fueled pressure tube. Analyses show that single tube rupture will not propagate to fail other tubes. Surveillance programs ensure continued protection from multiple process tube ruptures in the core.

G. EMERGENCY CORE COOLING SYSTEMS

The ECCS on the RBMK is designed to cool the reactor core in the event of an inlet pipe break, and must operate without availability of normal electric power. There are separate coolant inlet systems for each half of the reactor; the ECCS is designed to initially cool the damaged half of the reactor. The system is brought into operation by fast-acting electric gate valves, with electrical power for both valves and pumps being supplied by batteries. Water is obtained from two separate banks of pressurized storage tanks for the initial 100 seconds. A third leg uses water from an electric feed pump run from power available from the turbine-generator (TG) coast down. It was this feature that was under test when the Chernobyl accident occurred. For long-term afterheat removal, battery-driven cooling pumps supply water to both the damaged and undamaged halves of the reactor. Water is recirculated from the blowdown suppression pools beneath the reactor vessel.

Diesel-motor driven pumps provide the pressure to deliver water to the core in the N Reactor ECCS. When activated, the system draws down water from storage tanks for a once-through flow. If that supply is exhausted, a separate set of diesel pumps brings water to the system from the Columbia River. The initial stage of ECCS activation consists of opening valves and using compressed air activators to allow blow-down of the pressurized coolant. Because of the slow rate of heat-up in N Reactor and the margins to fuel damage from undercooling, the reflood system does not have to be fast-acting (i.e., within seconds). In addition to the main ECCS, there is a second backup cooling system in N Reactor. The Graphite and Shield Cooling System (GSCS) is a separate system of tubing that traverses the graphite stack to cool the graphite. Even for an assumed case where a LOCA occurred and the ECCS malfunctioned, the GSCS has sufficient cooling capacity to limit meltdown and stabilize a degraded core scenario. The GSCS is supplied with water by a set of diesel-driven pumps separate from the ECCS pumps. Like the ECCS, an unlimited supply of water is available from the river.

H. CONTAINMENT/CONFINEMENT

There is no containment or confinement enclosing the entire RBMK reactor. Mitigation of primary coolant system ruptures is accomplished by enclosing only certain portions of the primary cooling system inside pressure boundaries. The compartments enclosing the primary pump inlet and outlet headers are designed to accommodate the rupture of a single 30-cm (12-inch) diameter pipe. The piping from the outlet header to the fuel channel inlets is also enclosed in a pressure-tight compartment. All the remaining piping (fuel channels, channel outlets, steam drums, and steam lines) are outside any pressure boundary. The coolant circuit ruptures that occurred during the Chernobyl accident occurred in the piping outside the pressure-tight compartments.

N Reactor has a vented confinement system that encloses the entire reactor and primary cooling system. Its design is based on early venting of the non-contaminated steam resulting from any break (or multiple breaks) of the primary coolant piping. Following the steam venting, the vents are closed and any further venting is through filters designed to remove radioactive materials. A water spray activates automatically as part of this system, to provide cooling/condensation of the released steam and to remove radioactive materials from the atmosphere. This system is designed to accommodate the sudden double-ended rupture of the largest primary system pipe or manifold [e.g., a 66-cm (26-inch) diameter inlet manifold].

IV. OPERATING FEATURES COMPARISON

In addition to differences in physical plant design, the RBMK and N Reactor differ in their operating characteristics and procedures. The design gives the reactors different response characteristics. Administrative controls result in a different operating philosophy as well as operator control.

A. OPERATING CHARACTERISTICS

As stated earlier, an RBMK operates with a positive coolant void coefficient in the low power range (<20%). The reactor's coolant undergoes large changes in void content during normal operation. During the early development of the RBMK-type reactor, severe problems were encountered in maintaining the desired spatial power distribution because of the void coefficient. Subsequent reactors were modified to have lower graphite density, higher fuel enrichment, and a computer-assisted control system to allow for stable operation. Even with these changes, control rod withdrawal was restricted to prohibit removal of all rods during operation. The Soviets state that one of their most important rules is that the inserted rod worth must never be less than 15 equivalent rods (this is accomplished by having roughly a hundred rods partially inserted at all times). The reason for this restriction is that the magnitude of the positive void coefficient becomes larger as the inserted rod worth is reduced. Normally the Soviet reactors operate with an inserted rod worth of 30 equivalent rods. No alarms or automatic actions exist on the RBMK to indicate that inserted rod worth is below the minimum value.

N Reactor, with its negative coolant void coefficient, has a stable spatial power distribution. Spatial power distribution control is achieved by manual control alone. Stability is not affected by the amount of inserted rod worth.

For an RBMK, refueling is usually accomplished with the reactor on-line. With the reactor operating at full power, especially designed equipment is used to open an individual flow tube, extract the burned fuel from that tube, and insert a replacement fuel assembly. The ends of the flow tubes giving access to the reactor core for this operation, along with the associated equipment, are in the reactor building area outside of any confinement structures.

Refueling at N Reactor can only be accomplished with the reactor shut down. Burned fuel is pushed out one end of the process tube where it falls into a water-filled spent fuel basin. Spent fuel is discharged inside the closed confinement structure.

B. OPERATOR TRAINING

The Soviets state that their operators are well-educated, highly trained individuals. In fact, following the Three Mile Island (TMI) accident, the Soviets concluded there was no need to make changes in their operations since their operators were better trained than their U.S. counterparts. The exact nature of the Soviet training methods is not known. However, we do know there are no full-scale simulators for the RBMK. The Soviets have emphasized the fact that operator actions played a major role in the accident.

N Reactor operator training involves formal classroom instruction, use of a full-scale plant simulator, and a period of closely supervised on-the-job experience. A full-time training organization is in place to train new operators and to administer a program for scheduled, periodic recertification of all reactor operator personnel.

C. TEST CONTROL

A major factor in the Chernobyl accident was the failure to maintain control over the conduct of a special test. The test was conducted without all the proper approvals, control of the reactor was essentially turned over to an electrical engineer who knew little about plant operations, and the operators allowed the test to continue far outside the safe operating limits of the reactor. We do not know the details of the Soviet administration and control of special tests.

Tests in N Reactor are governed by a set of formal, documented requirements. Test descriptions and procedures require extensive review and approval before any test can be conducted. The review includes operations, nuclear and plant safety, and engineering. Tests are controlled by written procedures, and are directed by two responsible "Test Directors:" an Operations Test Director and a Technical Test Director. Agreement of both is required before proceeding with the steps of the test procedure. The Operations Test Director and Operations shift management have the authority and responsibility to unilaterally order test cessation or reactor shutdown if known, safe conditions cannot be ensured. Both test directors and a Safety manager must approve minor changes and the original review cycle is required for major changes. Any test that requires temporary modification of a technical specification or results in an "unreviewed safety question" must have formal approval of the DOE.

D. OPERATIONS CONTROL

The Chernobyl accident sequence is characterized by a number of operator actions that resulted in disabling emergency protection systems, disconnecting scram signals and operating outside known plant safety margins. The operators apparently removed or disconnected safety functions without approval from higher level plant management.

N Reactor operators function within the framework of a system of procedures and limits identified as Process Standards. Compliance is required during operation, unless the Process Standard limits are superseded by approved test conditions or changed according to a formal procedure. All tests or changes to limits must fall within the approved Technical Specifications; changes to Technical Specifications require review and approval of DOE. N Reactor operators have the ability to bypass some safety circuits from the control room, but controls must always comply with approved Technical Specifications. Procedures for use of bypasses limit use of this feature to periods of reactor shutdown (control rods and/or balls already inserted).

V. CHERNOBYL ACCIDENT DESCRIPTION

The following section contains the accident summary description, which was extracted directly from DOE/NE-0076, Appendix C. It indicates the operator actions and the design features of the Chernobyl plant that were contributing factors to cause the accident. The features of N Reactor that would have protected it from the accident are also identified.

A. GENERAL DESCRIPTION OF THE TEST THAT LED TO THE ACCIDENT

The accident at Chernobyl occurred during a planned test that was to be conducted at a power level of ~700 MWt as Unit No. 4 was being taken out of service for maintenance. In the test, it was desired to verify the ability of a TG to continue to provide electric power for internal operation of ECCS equipment, such as feedwater pumps, during a turbine rundown. This is interpreted to mean during loss of offsite power, where continuous power to vital safety equipment is needed until the emergency diesel generators become operational.

> **At N Reactor, emergency facilities are provided to accommodate a total and instantaneous loss of AC power. Therefore, tests of this type are not required and have not been performed.**

This test repeated a similar test conducted at Chernobyl-4 in 1985 during which the busbar voltage dropped much faster than the turbine rundown. In the present test, an electrical engineer was directing testing of a special generator field regulator designed to maintain higher busbar voltage for a prolonged time.

> **At N Reactor, two test directors are required: one from Operations and one representing the sponsor, and both are responsible for safely conducting the test. As a test proceeds from step to step, both directors must agree to proceed, either can terminate the test, and both must agree to minor changes in the test procedures; major changes require reanalysis, additional reviews, and reapproval.**

The reactor power operation was needed only to provide steam for initial turbine operation. The TG was being loaded primarily by four primary coolant pumps of the reactor; four additional pumps were being powered from outside sources so that even upon complete turbine rundown there would still be substantial coolant flow through the reactor for heat removal.

The test procedure prescribed that the ECCS be disengaged for the duration of the test.

> **In contrast, at N Reactor it is mandatory that the ECCS be operable (i.e., automatic activation armed and the system ready to operate) whenever the reactor is at power or undergoing startup.**

The procedure also prescribed that one of the two TGs powered by Unit No. 4 be taken out of service as an initial condition. After a delay of about nine hours, the test was initiated by shutting down steam flow to the remaining TG, initiating the rundown. According to the Soviet report, shutdown of the second TG should have automatically scrammed the reactor, which would have been appropriate since neither the reactor power nor continued steam generation should have played any further role in this test. However, this particular reactor scram signal, actuated by shutoff of steam flow to both TGs, had been blocked during the previous day "to have the possibility of repeating the test, if the first attempt proved unsuccessful." (They were concerned about xenon buildup.) Thus, the Soviet test was being conducted with the reactor continually generating power rather than automatically scrammed as planned.

At N Reactor, a change in a safety system cannot be made without a complete review and approval of the entire test procedure. This review includes a safety analysis of the proposed change. This process would have identified the potential hazard and the proposed change would have been disapproved.

At this point, in effect, three of the Chernobyl reactor's safety systems had been rendered inoperative while performing a safety test at power. Specifically, the ECCS had been disengaged and the automatic scram of the TG upon loss of steam flow had been bypassed, and a scram from steam drum thermal and level upset had been disabled.

In contrast, at N Reactor, safety systems are tested, maintained and qualified during shutdown and there is no need to bypass a safety system at power. Such bypasses are prohibited.

The reactor was manually scrammed 36 seconds (1:23:40) later when the operators observed the increasing power. By that time scram was too late in the RBMK; the damaging power excursion was underway, fed by the positive reactivity insertion caused by the increasing coolant boiling and the initial positive reactivity feedback of the rod scram.

B. CONDITIONS CONTRIBUTING TO THE ACCIDENT

The accident might still have been avoided, or considerably less severe, except for other circumstances. These circumstances involved a sequence of operator mistakes combined with a number of sensitive design features of the RBMK. Specifically, the local automatic power regulating rods (LAR) had been disengaged according to standard operating procedure for low-power operation, and hence were not available to counteract the voiding reactivity insertion. The global automatic power regulating rods (AR) were operational and were automatically inserted by the plant diagnostics and computer control system, partially compensating for the power rise but apparently without sufficient worth. Other absorber rods had been completely withdrawn previously to counteract xenon buildup and overcooling effects. When finally scrammed, these rods were too far out of the core to be of immediate worth and moved at too slow insertion speed (0.4 meters per second; about 20 seconds full insertion time) to terminate the overpower excursion.

> The operating procedures on all RBMK units require a certain control reactivity margin expressed as an effective number of control rods which must be in the core at all times. The normal requirement is 30 rods while the number properly positioned at this point in the test was set to 8. This serious violation of an operating procedure specifying the reactivity control margin did not prevent Chernobyl's reactor operators from continuing the test. In contrast, the worth of the N Reactor control rod system does not depend upon compliance with any administrative procedure. Moreover, the rod insertion speed is considerably faster with 75% of the rod inserted in less than 1.5 seconds. Both written requirements and training direct that deviation from an operating or test procedure must be reviewed and approved, and any significant deviation is sufficient to abort the test.

Because of the particular design of the RBMK control rod assemblies when the absorbers were fully withdrawn the control assembly duct contained 5 meters of graphite displacer centrally located in the 7-meter (23-feet) core with 1 meter (39.4 inch) of water above and below the graphite at the axial extremes of the core. In this configuration, it is calculated that the initial scram effect was not negative but positive reactivity insertion because of displacement of water, particularly at the bottom of the core. This circumstance probably caused a significant power shift to the bottom of the reactor.

> The design of the N Reactor control rods ensures that negative reactivity always results from rod insertion. Moreover, an independent and diverse shutdown system is always available. This system automatically drops boron carbide neutron absorber balls.

Additionally, the reactor was at very low power (7%) and very high coolant flow (>100%). Hence, the initial steam void in the core was exceedingly small, about 2% average. The Soviet report emphasizes that in this condition a small change in power causes the volumetric steam content to increase "many times more sharply than at nominal power." It is also believed that the void coefficient of reactivity is itself a function of void fraction, being larger for smaller void condition. These two factors would combine to cause the void reactivity insertion to be particularly severe under the conditions during which the test was run.

> The coolant void coefficient in the RBMK units is positive, which introduces the autocatalytic potential from an increase in power which will increase the coolant void which will further increase the power, etc. In contrast, at N Reactor the coolant temperature coefficient is negative, ensuring that any increase in power will increase the coolant temperature which will automatically decrease the power. The N Reactor coolant does not boil. If boiling should occur, the result would be a negative change in reactivity owing to the negative void coefficient. All other prompt reactivity coefficients also add negative reactivity as temperature increases.

Immediately before the test, the operator "sharply reduced the feedwater flowrate." Hence, the temperature of the water to the main coolant pumps and to the core inlet was increasing since suction was now primarily from the steam separator drum. Increasing water temperature at the core inlet may have exacerbated the steam generation in the core.

In summary, the circumstances leading to the accident were as follows: (1) the reactor was operating (though it should have been scrammed from the onset); (2) the coolant flow rate was decreasing leading to additional steam generation in the core; (3) the coolant inlet temperature was increasing, leading to more rapid steam generation in the core; (4) the initially over-cooled core with close to zero steam content was in a particularly vulnerable state with regard to void related reactivity insertion; (5) the automatic power regulating system was incapable of counteracting the void reactivity insertion; (6) the rods available for scram were located fully out of the reactor core in a region of low initial worth; and (7) the scram itself is calculated to have caused a sizeable reactivity insertion initially.

C. TRANSIENT OVERPOWER EXCURSION

Under the conditions described, a net positive reactivity caused by increasing coolant boiling in the core, resulted in a power rise. At first the rate of power rise was slow. At 1:23:40 the reactor was manually scrammed, but without the desired shutdown effect. At 1:23:43 the power was reported to have exceeded 520 MW (up from 200 MW at the beginning of the test), and the "runaway period came to be much less than 20 seconds." Actually the reactor was already experiencing a prompt critical power excursion at that time. It is stated that "only the (fuel) Doppler effect partially compensated for the reactivity introduced at this time." The power transient calculated by the Soviets had a peak power of 350,000 MW (110 x full power) and a full width at half maximum (FWHM) of 0.8 seconds. The Soviets indicate that the energy release in the fuel "exceeded 300 cal/g."

The effect of the power burst is described in the Soviet report as follows: "[The power rise] led to an intensive steam formation and then to nucleate boiling, overheating of the fuel, melting of the fuel, a rapid surge of coolant boiling with particles of destroyed fuel entering the coolant, a rapid and abrupt increase of pressure in the fuel channels, destruction of the fuel channels, and finally an explosion which destroyed the reactor and part of the building and released radioactive fission products to the environment."

> A catastrophic, autocatalytic power excursion such as this cannot occur at N Reactor because of the strong negative power coefficient. The presence of two independent nuclear control shutdown systems makes it unlikely that any excursion that could occur would damage the fuel. This leaves considerable margin to core disruption and any possibility for release of fission products to confinement.

D. CONSEQUENCES OF THE OVERPOWER TRANSIENT

The above description suggests that fuel-coolant thermal interactions (FCIs) occurred from the sudden mixing of hot (including molten) UO_2 fuel and coolant in the channels, and that the subsequent pressurizations caused channels to rupture. (The plausibility of this was subsequently confirmed through the application of Argonne National Laboratory accident analysis codes.) Rupturing the channels would initiate blowdown of steam and flashing water from about 6.5 MPa pressure to the surrounding volume(s). The Soviet's report is silent on the suspected locations of ruptures. There are thought to be four principal locations:

- Upward slug expulsion from the pressurization zone has been shown to be capable of breaching the top end cap of the operating channel at the refueling machine attachment, initiating upward blowdown and fuel dispersal into the uncontained region immediately below the removable refueling floor slabs.

- The zirconium-to-steel weld joints immediately above and below the active fuel zone of the core are thought to be weak points; failures of the piping at either or both of these locations would cause steam blowdown into the region of graphite blocks in the sealed reactor space.

- The zirconium-alloy pressure tube is likely to fail locally at the region of the pressurization event due both to the overpressure itself and to thermal effects of fuel impingement on the pressure tube wall. This failure location would cause steam blowdown into the central zone of graphite blocks in the sealed reactor space.

- It is also possible that shock pressures and water hammer pressures propagated upstream as a result of the pressurization events in the operating channels and damaged piping at the inlet side of the reactor; blowdown of steam and flashing water would enter the containment cell (65 psig) designed to vent to the pressure suppression pool.

Any or all of these types of ruptures could have occurred from the initial fuel failure events. The ruptures of the top end caps would have caused the immediate blowdown and discharge of fuel debris upward into the refueling building and possibly directly into the atmosphere. Multiple tube ruptures into the reactor space would quickly overpressurize this region since its overpressure relief protection is sized for failure of only one channel. Upon overpressurization this region would fail structurally, as is known to have occurred. Some of the graphite blocks were ejected, and the reactor core was opened to the atmosphere.

It is reported that two explosions were heard, "One after another," and that "hot fragments and sparks" flew up above the plant, described elsewhere in the report as "fireworks of flying hot and glowing fragments." The mechanism for this dispersal may have involved the upward-directed channel ruptures at their tops, the overpressurization failure of the reactor vault and subsequent blowdown of that region, or a subsequent explosion of some other origin. There are statements in various parts of the report attesting that fuel debris was ejected into the atmosphere; e.g., "As a result of explosions in the reactor an ejection of core fragments heated to a high temperature... (occurred)." The report also speculates that a chemical explosion could have occurred "after unsealing of the reactor space." These statements are not necessarily contradictory; they indicate uncertainties in the actual sequence and consequences of multiple events. However, observations made by Russian engineers using video cameras on robots indicated no evidence of a hydrogen burn.

> **It is important to note that there is no specific evidence that either a hydrogen explosion or graphite fire was a contributor to the reactor disruption up to this point.**

E. CHERNOBYL PLANT FEATURES THAT EXACERBATED ACCIDENT CONSEQUENCES

Although the Soviets place heavy blame for the accident on the individuals who planned and carried out the TG rundown test and on the reactor operators rather than on equipment failures or design shortcomings, it is clear that the following features of the RBMK reactor design contributed to the severity of the accident.

1. The speed of insertion of the scram rods is much too slow to provide adequate protection against emergency situations such as arose during the accident. The Soviet approach is that large numbers of rods compensated for their slow rate of insertion. The insertion rate is stated to be 0.4 meters (15.8 inch) per second, and since the total core height is 7 meters (22.9 feet), it takes about 18 seconds for complete scram rod insertion.

   > **In contrast, the comparable scram time for the control rod system in N Reactor is less than three seconds. In addition, N Reactor has a completely independent ball drop system that has sufficient insertion speed to prevent fuel damage even if the rod system failed to respond.**

2. There was no positive stop on the absorber rods to limit their withdrawal. The rods were so far out of the core that they did not immediately insert negative reactivity as depended upon when the reactor was scrammed. To the contrary, the rod design and initial position caused a "positive scram," i.e., there was a major positive reactivity insertion upon scram, rather than shutdown.

   > The "positive scram" appears to be unique to the RBMK design and to the particular state of the reactor; there is no positive scram effect in N Reactor.

3. Many parts of the reactor piping system pass through areas where there was no containment whatsoever. This includes the top sections of the operating channels, steamwater lines, steam line piping, and parts of the feedwater and return line piping. It is indicated that fuel debris was released directly to the atmosphere at Chernobyl-4 as a result of pipe ruptures and blowdown into uncontained regions.

   In contrast, N Reactor has a large volume confinement system that totally encloses the reactor and the primary coolant system. Release of coolant, fuel or core debris from the primary system would be limited to the confinement structure.

4. The zirconium-to-steel transition welds are thought to be weak points in the RBMK piping system, although it is uncertain whether this played any role during the accident. The welds have a heatup rating limited to 15°C/hour which may have been exceeded during the accident. Since rupture of the piping at the welds would cause blowdown into the sealed reactor space, the welds are a potential cause of failing the vault during the accident involving multiple ruptures.

   There are no comparable weld joints within the N Reactor shield enclosure. Previous analyses indicate that an accident caused by a guillotine rupture of a process tube in N Reactor would terminate without propagation. These analyses have been reviewed and updated and surveillance of process tubes has been further emphasized to ensure that multiple tube failures will not result from any plausible initiating event.

5. With the primary cooling system damaged in an RBMK unit, there is no mechanism for removing the heat generated by either fission product decay, metal-water reactions, or graphite oxidation.

   N Reactor has a separate system (GSCS) that cools the graphite moderator and which could stabilize and cool the core within a few hours after total cooling loss. This heat removal mechanism would have several very important benefits: it would limit the amount of fuel that would heat up and fail to about one-third the loading; it would reduce (temperature dependent) rates of metal-water reactions and graphite oxidation so that they would not significantly increase the consequences of the accident; and it would maintain damaged fuel inside the pressure tubes.

VI. BIBLIOGRAPHY

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